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Non-overwintering cover crops: a significant source of N

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Abstract

The effects of cover crops on the yield of potatoes and sugar beets were studied in 11 experiments on clay soils during the 80-ties. Cover crops consisted of Italian ryegrass fertilized with 0 (G0), 100 (G100) and 200 (G200) kg nitrogen (N) ha^{-1} and red clover (RC) without N. All cover crops were undersown to winter wheat and ploughed down in the first half of November. On average, G0, G100, G200 and RC had then accumulated 22, 93, 125 and 57 kg N ha^{-1}, respectively, in the aboveground plant parts. G0 cover crops tended to immobilize soil mineral N in spring and generally had insignificant effects on the yields of potatoes and sugar beets, whereas G100, G200 and RC increased the N yields and marketable yields significantly. Effects were mainly attributable to the release of N. The fertilizer value of cover crops was evaluated by their effect on (1) economic optimum N rates, (2) the marketable yield and (3) the N yield when no mineral fertilizer N was supplied. The last two methods appeared to be most appropriate for the present experiments. Fertilizer values ranged from −21 to 108 kg N ha^{-1}, depending on the type of cover crop and the calculation method. About half of the N accumulated in aboveground parts of the cover crop was available to potatoes and sugar beets from G100 when evaluated by its effect on N yields. From G200 this was even more, although this may partly have resulted from the transfer of fertilizer N that had not been taken up by the cover crop. Due to a high content of N in roots and stubble, RC provided, on average, almost double the amount of N accumulated in the aboveground plant parts. Cover crops also had a minor positive effect on grain yields of winter wheat following potatoes and sugar beets. Our results indicated that at least 35% of the aboveground N in Italian ryegrass cover crops was not utilized within the first 18 months after their incorporation.

Keywords: apparent recovery, cover crop, fertilizer value, nitrogen, residual effect

Introduction

For a long time cover crops were mainly advocated to provide additional forage in mixed farming systems and to improve soil fertility (Renius & Lütke Entrup, 1985). More recently, environmental aspects have received attention, as cover crops can scavenge the soil mineral nitrogen (SMN) left by preceding crops or released from the ongoing decay of soil organic matter. Without cover crops much of this SMN can be lost during winter (Martinez & Guiraud, 1990; Rogasik *et al.*, 1992; Thorup-Kristensen, 1994; Schröder *et al.*, 1997). Cover crops can also reduce the loss of nitrogen (N) from autumn-applied manure (Steffens & Vetter, 1984). However, potential production of cover crops and their subsequent effect on the reduction of N losses are markedly determined by weather conditions (Elers & Hartman, 1988; Fielder & Peel, 1992; Soerensen, 1992). Hence, cover crops can only act as a sink for N from manure if applied in late summer after early maturing crops leaving small amounts of SMN such as cereals (Neeteson, 1995; Schröder *et al.*, 1996). Without N inputs, cover crops after cereals may even fail to grow.

Storing substantial amounts of N, alone, is not a guarantee of long-term reduction of N loss, as the mineralization of a cover crop is not always properly synchronized with the demand for N of a following crop (Thorup-Kristensen, 1994; Schröder *et al.*, 1997). Synchronization of supply and demand is determined by pedoclimatic conditions, cover crop species and management factors such as fertilization, killing date and depth of incorporation.

Carbon (C) to N ratios of cover crops increase with their age (Laurent & Mary, 1992; Wyland *et al.*, 1995). Initially, the remainders of some cover crop types may immobilize rather than release N when left intact during winter (Scott *et al.*, 1987; Wagger, 1989a, 1989b; Martinez & Guiraud, 1990; Francis *et al.*, 1995). Consequently, the chances of an effective transfer of cover crop N to the next growing season are not by definition larger when cover crops overwinter than when they are killed in autumn. Killing in autumn is most common for farms on clay soils where fall ploughing is preferred to spring ploughing. Too early a destruction of cover crops, however, may expose cover crop N to early mineralization, nitrification and subsequent losses, especially in mild and wet winters. Hence, the N contribution of cover crops to following crops is uncertain. SMN measurements in early spring do not always provide adequate information because lack of change in SMN may indicate either that cover crop N has been lost permanently, leached into layers not included in the sample, or not yet mineralized. Consequently, farmers who adjust their N rates to SMN supplies in spring, do not often account for this N source and apply just as much N as they would have done without cover cropping. Such a fertilizer management strategy ignores the potential for financial savings and is environmentally as questionable as a strategy without cover crops. Researchers, too, disagree how to credit the fertilizer value of a cover crop. A common method consists of a comparison of the N yield of an unfertilized test crop preceded by a cover crop with the N yields from a N response curve of the test crop preceded by fallow.

As the effect on the N yield is not necessarily equivalent to the effect on the marketable yield, especially farmers may argue that it may be better to deduce the fertilizer value from the marketable yield response. Lory *et al.* (1995) concluded that even this method can be incorrect, as it ignores non-N effects. Instead, they advocated to use the difference in the economic optimum N rates in order to discriminate N from non-N effects. In their view, N response curves have to be established for the test crop both without and with a preceding cover crop.

Without elucidation of the aforementioned aspects, cover crops may be creditted incorrectly. From 1982 to 1989 we carried out experiments (1) to quantify the N tranfer by cover crops from one season to another and (2) to compare the fertilizer values of cover crops determined according to various methods.

Materials and methods

Experimental design

Continuous experiments were conducted from 1982 to 1989 on two clay soil (38% of the particles < 16 μm) sites in Randwijk (51° 52' N, 5° 45' E) and two clay soil (29% of the particles < 16 μm) sites in Nagele (52° 37' N, 5° 45' E), The Netherlands.

The groundwater table during summer is at a constant depth of about 150 cm. Additional soil characteristics are presented in Table 1.

All experiments took place in a wheat/potato/wheat/beet rotation (Table 2). Ware potatoes (*Solanum tuberosum L.* cv. Bintje) and sugar beets (*Beta vulgaris L.*, cv. Monohil or Ovatio) in these rotations were preceded during winter by either fallow or a cover crop. Four types of cover crops were grown in each experiment: Italian ryegrass (*Lolium multiflorum L.*, cv. Tetila, seed rate 30 kg ha^{-1}) with 0 (G0), 100 (G100) and 200 (G200) kg N ha^{-1} (applied after the harvest of wheat as calcium ammonium nitrate (CAN)) and red clover (*Trifolium pratense L.*, cv. Rotra, seed rate 15 kg ha^{-1}) without N (RC). The G100 and G200 treatments were included to simulate situations where cover crops are used to wrap up manure-N. The N rates applied to our G100 and G200 cover crops are more or less representative for the input of ammoniacal N when Dutch arable farmers are using slurry on cereal stubbles.

All cover crops were undersown to winter wheat (*Triticum aestivum L.*, cv. Durin, Arminda or Pagode) between mid April and mid May and resumed growth in August when wheat matured. In the last year of each experiment no undersowing to wheat took place. Plots of cover crops and fallowed plots were ploughed in the first half of November. Wheat straw and sugar beet tops (including leaves) were removed from all plots. Potatoes and sugar beets were planted in April and harvested in September and mid October, respectively. All sites received annual dressings of about 50 kg P and 210 kg K ha^{-1}. Winter wheat crops received uniform blanket dressings of N (applied as CAN) at rates considered best by the local farm manager. Rates varied from 100 to 200 kg N ha^{-1}.

The response of potatoes and sugar beets to cover crops was studied four and seven times, respectively (Table 2). For that purpose, five N rates (applied as CAN in

Table 1. Soil characteristics of the upper 25 cm layer in 1981–1982.

Site	Org. matter (%)	pH-KCl	K-HCl (mmol K kg^{-1} soil)	P-water (mg P liter^{-1} soil)
Randwijk, 1 and 2	2.1	7.6	2.6	28
Nagele, 1 and 2	3.0	7.3	1.8	12

Table 2. Crop rotation (w=wheat, p=potatoes, s=sugar beets) on the four sites.

Site	Year:								
	1981	1982	1983	1984	1985	1986	1987	1988	1989
Randwijk, 1	w	p	w	s	w	p	w	s	w
Randwijk, 2		w	s	w	p	w	s	w	
Nagele, 1	w	s	w	p	w	s	w		
Nagele, 2		w	s	w					

spring) were superimposed on the four cover crop treatments and the fallow treatment. N rates were 0, 60, 120, 180 and 240 kg N ha^{-1} in all experiments in Nagele, 0, 80, 160, 240 and 320 kg N ha^{-1} in the experiments with potatoes in Randwijk, and 0, 50, 100, 150 and 200 kg N ha^{-1} in the experiments with sugar beets in Randwijk. The consecutive N rates are referred to as N0, N1, N2, N3 and N4.

The residual effects of cover crops and N rates applied to potatoes and sugar beets, were determined from grain yields in all but two (Randwijk, site 1 experiment 1985 and site 2 experiment 1986) wheat crops following potatoes or sugar beets.

Experiments were set up as split plot trials with four replicates with cover crop and fallow treatments as main plots and N rates on sugar beets and potatoes as subplots. Subplot size amounted to 6 × 11.5 m in Randwijk and 6 × 9 m in Nagele. Only the inner 3 × 8.5 and 5 × 8 m in Randwijk and Nagele, respectively, were used for the assessment of yields and SMN. Treatments remained exactly in place on each site.

Weather

The average daily temperature during the period of cover crop growth (September-October) ranged from 11.5 °C in 1986 to 13.4 °C in 1982. Average daily temperature and summed rainfall during winter (November-February) ranged from 1.8 °C in 1985 to 5.4 °C in 1987 and from 174 mm (Randwijk, 1984–1985) to 357 mm (Randwijk, 1987–1988), respectively. Mild winters were associated with above-normal precipitation.

From March to August, average daily temperature ranged from 11.7 °C in 1987 to 13.2 °C in 1983. Summed rainfall during this period ranged from 262 mm (Randwijk, 1982) to 550 mm (Randwijk, 1987).

Observations

Aboveground dry matter (DM) yields of cover crops were assessed (N0 subplots only) just before ploughing by cutting and weighing plant material from a 15 m^2 area. Subsequently, the DM content was determined by drying a 500 g subsample for 4 hours at 70 and 8 hours at 105 °C. Kjeldahl-N content was assessed in the dried material. We assumed that the C content of the cover crop DM was 0.4 kg kg^{-1} (Klimanek, 1990; Thorup-Kristensen, 1994; Wyland *et al.*, 1995). On the Randwijk sites 1 (experiment 1986) and 2 (experiment 1987) the N yield of the G0 treatment was less than 10 kg ha^{-1} and, therefore, the crop was not sampled. Results from these experiments were omitted in the calculations for which N yields of all four cover crop treatments were needed but included in results concerning the response of potatoes, sugar beets and wheat.

The marketable fresh yield of potatoes was defined as the summed weight of tubers not passing a 35 mm grid sieve. The total N yield was calculated from the total fresh yield and the Kjeldahl-N content of a representative sample from all tubers, including the < 35 mm class. The sugar yield of beets was calculated by multiplication of the weight of the beets and their sugar content. N yields of beets and tops (including leaves) were determined by weighing the fresh yield of each of both fractions, followed by the assessment of their DM (drying for 4 hours at 70 and 8 hours at 105 °C) and Kjeldahl-N contents. The impurity of beet roots was characterized by the α-amino N content.

SMN (NO_3-N and NH_4-N; 0–30, 30–60, 60–100 cm depth) was determined in March in a composite of core samples from all four replicates on an Autoanalyzer II. SMN measurements took place in five of the eleven experiments in N0 subplots of fallow, G0, G100 and RC plots. In four experiments G200 plots were included.

Calculations

A quadratic response model relating fertilizer N rates to yields (Cerrato & Blackmer, 1990) was fit to the marketable yield data of potatoes and sugar beets. The coefficients of this model were significant ($P < 0.10$) in all but the 1986 experiment of Randwijk site 1 and the 1987 experiment of Randwijk site 2. Economic optimum N rates (EONR, kg ha^{-1}) were determined by setting the first derivative of the reponse function equal to a price ratio of 5 and 1.5 kg kg^{-1} N for marketable potatoes and sugar, respectively.

The response of the N yield to fertilizer N on fallow plots was best described with quadratic and linear functions (Cerrato & Blackmer, 1990) for potatoes and sugar beets, respectively, yielding relationships with significant ($P < 0.05$) coefficients. The apparent recovery of fertilizer N at the EONR (ANR_{EONR}, %) was calculated as the difference in the fitted N yield of a crop preceded by fallow at the EONR ($NY_{EONR,FW}$) and the N yield of an unfertilized crop preceded by fallow ($NY_{N0,FW}$) and expressed as a percentage of the EONR:

$$ANR_{EONR} = 100 \times (NY_{EONR,FW} - NY_{N0,FW}) / EONR \quad (1)$$

The apparent recovery of cover crop N (ANR_{CC}, %) was calculated as the difference in measured N yield of an unfertilized crop preceded by a cover crop ($NY_{N0,CC}$) and an unfertilized crop preced by fallow ($NY_{N0,FW}$) and expressed as a percentage of the aboveground N yield of the cover crop (NYCC):

$$ANR_{CC} = 100 \times (NY_{N0,CC} - NY_{N0,FW}) / NYCC \quad (2)$$

The fertilizer value of the cover crop (FV, kg N ha^{-1}) was calculated according to three methods which are illustrated in Figure 1. First, the fertilizer value (FV_1) was

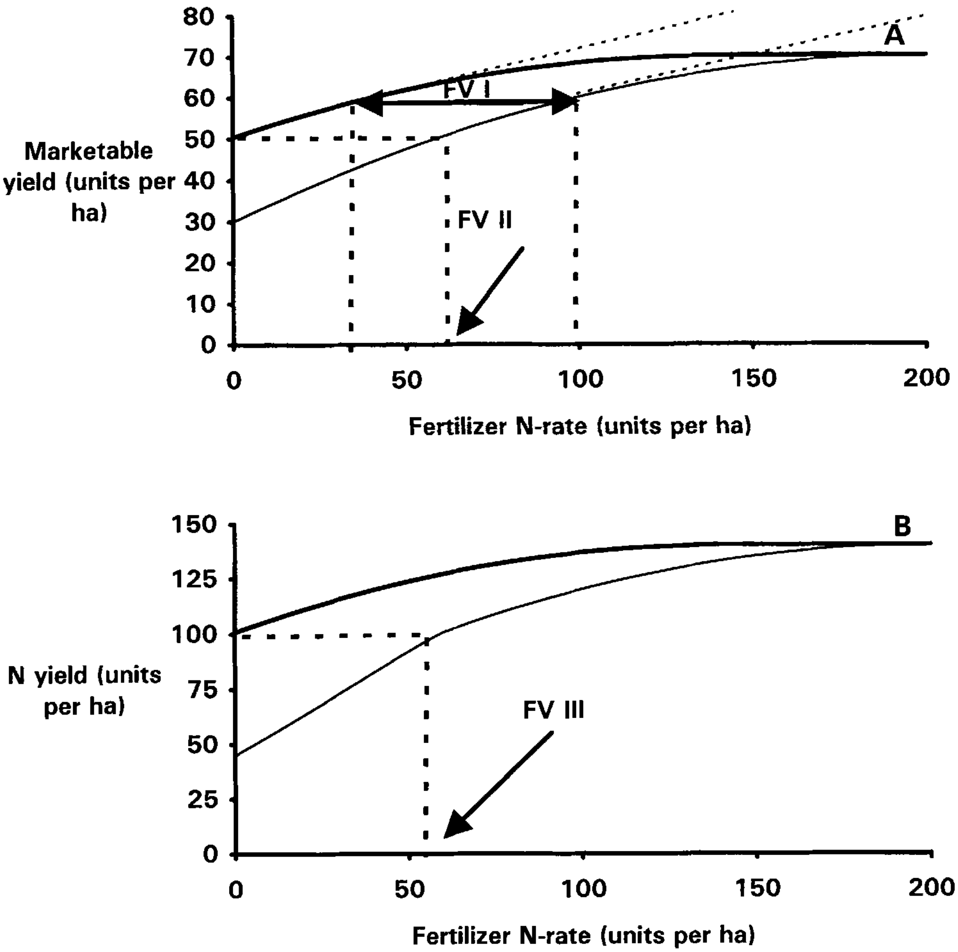


Figure 1. Response of the marketable yield (A) or N yield (B) to fertilizer N and the method applied for the calculation of the fertilizer value of cover crops (—— = preceded by fallow; —— = preceded by cover crop).

defined as the difference in the EONR for crops preceded by fallow ($EONR_{FW}$) and the EONR for crops preceded by a cover crop ($EONR_{CC}$):

$$FV_I = EONR_{FW} - EONR_{CC} \qquad (3)$$

Second, the fertilizer value (FV_{II}) was determined by solving the marketable yield response function of a crop preceded by fallow for the marketable yield of an unfertilized crop preceded by a cover crop ($Y_{N0,CC}$):

$$Y_{N0,CC} = (a \times (FV_{II})^2) + (b \times (FV_{II})) + c \qquad (4)$$

where a, b, and c are the coefficients of the response function.

Third, the fertilizer value (FV_{III}) was determined by solving the N yield response function of a crop preceded by fallow for the N yield of an unfertilized crop preceded by a cover crop ($NY_{N0,CC}$):

$$NY_{N0,CC} = (d \times (FV_{III})^2) + (e \times (FV_{III})) + f \tag{5}$$

where d, e and f are the coefficients of the response function.

FV_I was not determined on Randwijk site 2 (experiment 1983) and Nagele site 1 (1984) where EONR's could not be determined because yields showed no diminishing response to N. FV_{II} was not determined on Randwijk site 2 (experiments 1983 and 1987) where Equation 4 could not be solved for the observed $Y_{N0,CC}$'s.

For each of the three calculation methods, the relative fertilizer value of a cover crop (RFV) was defined as the fertilizer value (FV) expressed as a percentage of the aboveground N yield of the cover crop (NYCC):

$$RFV = 100 \times FV / NYCC \tag{6}$$

Results

Nitrogen yield of cover crops

When averaged over the years, the amount of N that accumulated in the cover crops ranged from 22 kg for G0 to 125 kg ha^{-1} for G200. C to N ratios ranged from 27 for G0 to about 15 for the three other cover crops (Table 3).

N yields of Italian ryegrass responded markedly to fertilizer N. On average, 71 kg N ha^{-1} (range 52–107) of the 100 kg N ha^{-1} rate on grass (G100) was recovered in the aboveground plant parts. A further increase of the rate up to 200 kg N ha^{-1} (G200) resulted in an additional uptake of 32 kg N ha^{-1} (range 9–58). N yields varied within N treatments and showed significant ($P < 0.05$) relationships with the accumulated precipitation between May 1 and August 31 (Figure 2). Variation could not be explained by a single weather-related factor after the harvest of wheat such as the accumulated temperature (> 5 °C, range: 497–896 degree days), precipitation (range: 87–290 mm) or global radiation (range: 554–912 MJ m^2).

Table 3. Aboveground N yield of cover crops (kg ha^{-1}), C to N ratio in the first half of November and the apparent surplus of fertilizer N (kg ha^{-1}) applied to Italian ryegrass (average of the 9 experiments).

Cover crop type	N yield	C to N ratio	N surplus
Grass + 0 N	22	27	–
Grass + 100 N	93	16	29
Grass + 200 N	125	13	97
Red clover	57	15	–
LSD ($P < 0.05$)	16	4	

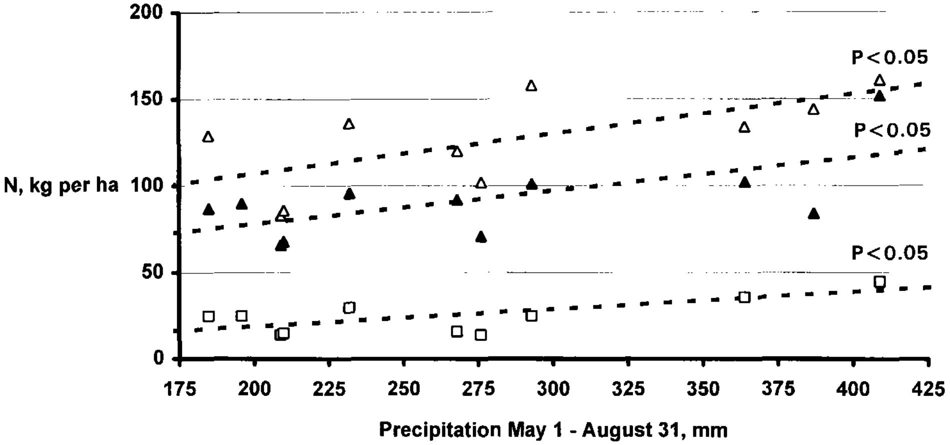


Figure 2. N yield of undersown Italian ryegrass cover crops as affected by the accumulated precipitation (mm) between May 1 and August 31 and by fertilizer N (average of 11 experiments; □ = G0, ▲ = G100, △ = G200).

Cover crop effects on soil mineral nitrogen in spring

The amount of aboveground cover crop N that had been ploughed in, was not fully reflected in an increase of SMN in the upper 100 cm in the subsequent spring. G0 cover crops even tended to reduce SMN. The recovery of cover crop N was less incomplete, however, when evaluated by the effect of cover crops on the N yield of potatoes and sugar beets, especially when it is taken into account that these crops only take up a fraction of the N mineralized from from cover crops, similar to fertilizer-N. Red clover in particular, had a much larger effect on the N yield of following crops than indicated by the change of SMN in spring, suggesting that cover crops had not fully been mineralized by the time SMN was assessed in March (Figure 3). Measurements of SMN in the four experiments were G200 plots were included, indicated that the soil of G200 plots contained about two times more SMN (62 kg ha^{-1}) than could be explained by the difference in aboveground N uptake between G100 and G200 cover crops (33 kg ha^{-1}) in those years. This may point at a partial carry-over of fertilizer N from autumn to spring.

Response of potatoes and sugar beets to cover crops and fertilizer nitrogen

The N yield of unfertilized (N0) potatoes and sugar beets responded positively to G100, G200 and RC cover crops in all experiments. This response was significant ($P < 0.05$) in 7, 11 and 10 out of 11 experiments for the G100, G200 and RC treatments, respectively. When following G0 cover crops, however, N yields were not significantly affected except for site 1 where N yields responded negatively ($P < 0.05$) in 1982 and positively ($P < 0.05$) in 1988. EONR$_{FW}$'s amounted to 250 and 135 kg N ha^{-1}, on average, for potatoes and sugar beets, respectively. ANR$_{EONR}$'s were approxi-

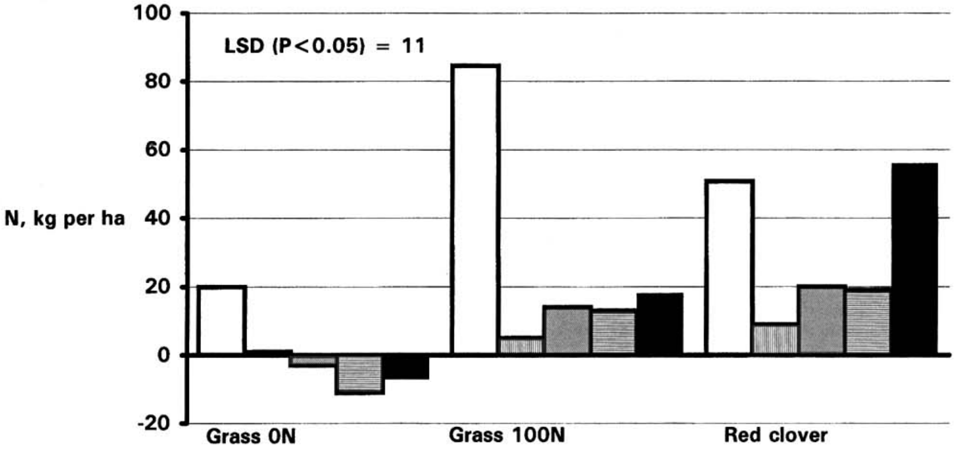


Figure 3. Aboveground N yield of cover crops and change in soil mineral N in spring (SMN) in various layers and the N yield of a following crop expressed as the difference with the fallow treatment (average of 5 experiments; □ = N yield of cover crop, ▨ = change of SMN in 0–20 cm layer, ▥ = change of SMN in 0–60 cm layer, ▤ = change of SMN in 0–100 cm layer, ■ = change of the N yield of the subsequent crop).

mately 70% for sugar beets and 40% for potatoes.

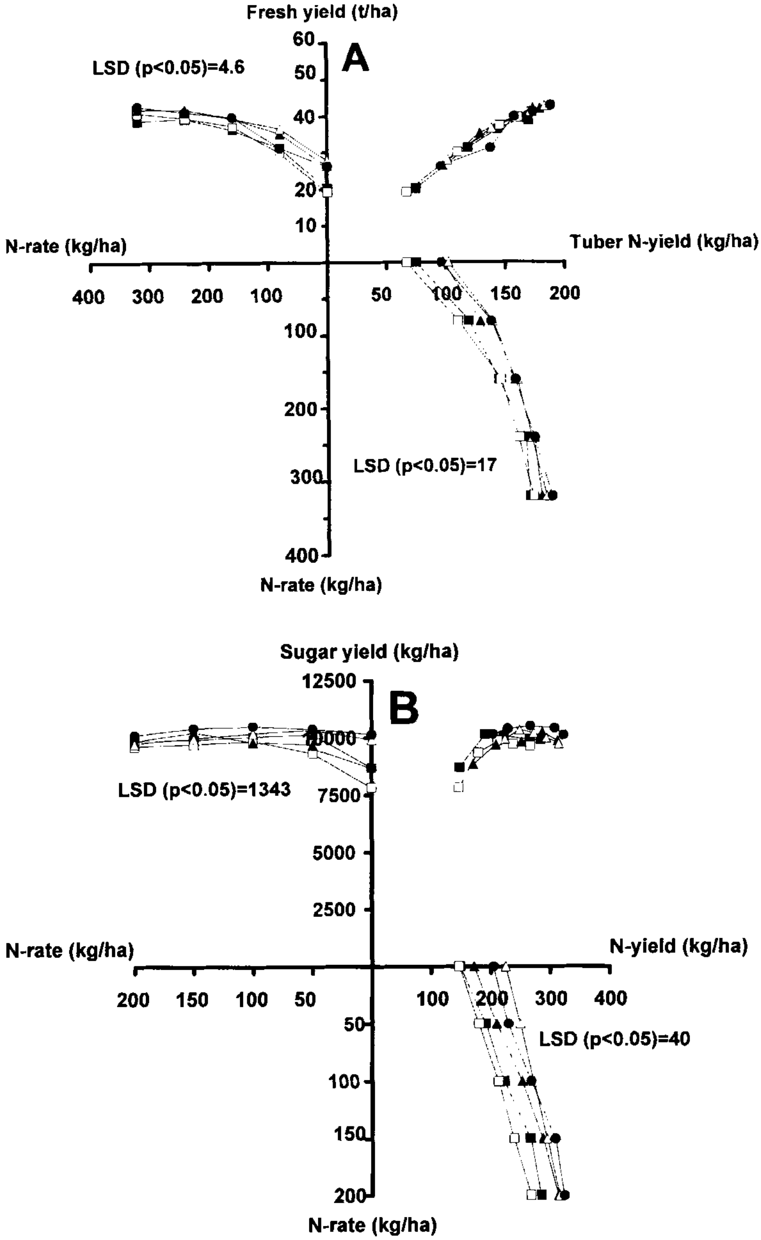
A stepwise analysis of the relationships between N rates, N yields and marketable yields (Figure 4A–4D), indicated that cover crop effects could almost fully be interpreted in terms of the availability of N, as similar amounts of marketable yield were produced per kg N taken up on fields preceded by fallow or cover crops.

The α-amino N content of beet roots increased with the amount of N taken up. It did not make any difference, however, whether this N originated from mineral fertilizer or from cover crops (Figure 5).

Apparent recovery and fertilizer value of cover crops

In agreement with the recoveries of fertilizer N, sugar beets recovered a larger fraction of the cover crop N than potatoes. On average, 30% and 42% of the aboveground 93 kg N ha^{-1} that had accumulated in G100 cover crops, was recovered by potatoes and sugar beets, respectively. Corresponding values for G200 cover crops were 28% and 70%. Recovery of N from RC was, on average, larger than 100% (Table 4).

Fertilizer values (FV) varied with cover crop type and calculation method as shown by the results from the seven experiments where all three methods could be used concomittantly, including the calculation of relative fertilizer values (Table 5). Fertilizer values decreased in the order $FV_{III} > FV_{II} > FV_{I}$. Differences between FV_{III} and FV_{II} originated from the experiments with sugar beets rather than from experiments with potatoes (Figure 6). For sugar beets, the N yield responded much stronger to N (applied as either mineral N or cover crop N) than the marketable yield (Figure 4B and 4D). Consequently, the fertilizer value deduced from the marketable



yield response curve (FV_{II}) was constraint by an upper limit whereas the fertilizer value deduced from the N yield response (FV_{III}) reflected the increase in available N over a much broader range.

G0 cover crops had a negative fertilizer value. G100 and G200 cover crops showed

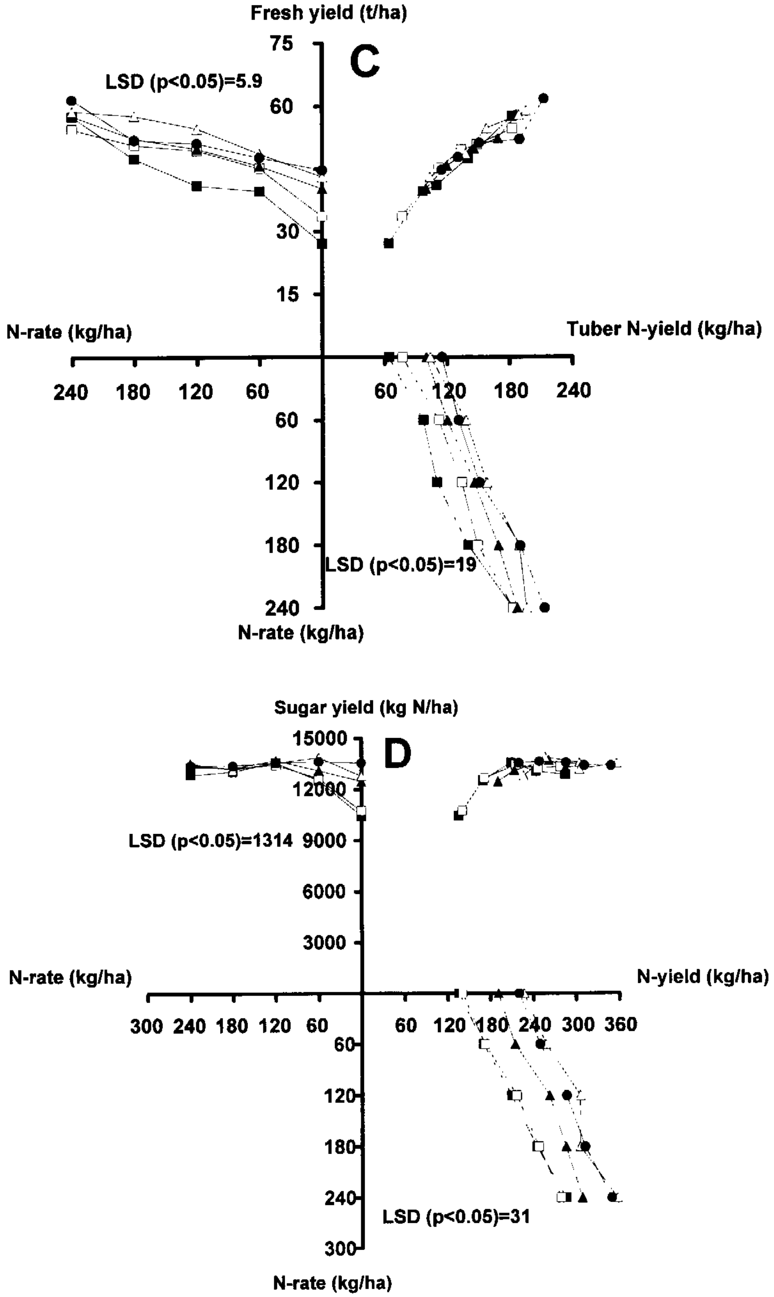


Figure 4. Relationships between N fertilizer rates, N yields and marketable yields for the experiments on potatoes in Randwijk (A), on sugar beets in Randwijk (B), on potatoes in Nagele (C) and on sugar beets in Nagele (D): ■ = fallow, □ = G0, ▲ = G100, △ = G200, ● = RC.

Table 4. Apparent recovery of aboveground cover crop N (ANR$_{CC}$, % [Equation 2]) by potatoes (average of 3 experiments) and sugar beets (average of 6 experiments).

Cover crop type	Following crop	Apparent recovery
Grass + 0 N	potatoes	–29
Grass + 100 N		30
Grass + 200 N		28
Red clover		151
LSD ($P < 0.05$)		67
Grass + 0 N	sugar beets	6
Grass + 100 N		42
Grass + 200 N		70
Red clover		124
LSD ($P < 0.05$)		30

FV$_{III}$'s about half the amount of fertilizer N applied to them in the preceding year. The FV$_{III}$ of RC was equivalent to that of G200 cover crops.

The relative fertilizer value (RFV) varied with the calculation method and ranged from –22% to –104% for G0 cover crops (indicating that they consumed rather than supplied inorganic N) and from 2% to 94% for G100 and G200 cover crops. RFV$_{II}$ and RFV$_{III}$ for RC exceeded 100% indicating that roots and stubbles contributed substantially to the release of N.

Residual effects on winter wheat

Grain yields of winter wheat following potatoes and sugar beets responded positively ($P < 0.05$) to both former N rates and cover crops (Figure 7). All cover crops, including G0, had a minor positive effect in the second year after their incorporation. This effect was observed in all but one experiment. Cumulative effects in the course

Table 5. Fertilizer values (FV [Equations 3, 4 and 5]) and relative fertilizer value (RFV [Equation 6]) of cover crops obtained by three different calculation methods (average of 7 experiments; in parentheses average FV$_{III}$ of all 11 experiments).

	Fertilizer value (kg ha^{-1})			Relative fertilizer value (%)		
	FV$_I$[1]	FV$_{II}$[2]	FV$_{III}$[3]	RFV$_I$	RFV$_{II}$	RFV$_{III}$
Cover crop type						
Grass + 0 N	–21	–14	–1 (–2)	–104	–73	–22
Grass + 100 N	5	42	52 (51)	2	44	56
Grass + 200 N	44	66	108 (101)	35	54	94
Red clover	44	89	97 (89)	50	195	197
LSD ($P < 0.05$)	36	79				

1) see Equation 3, 2) see Equation 4, 3) see Equation 5

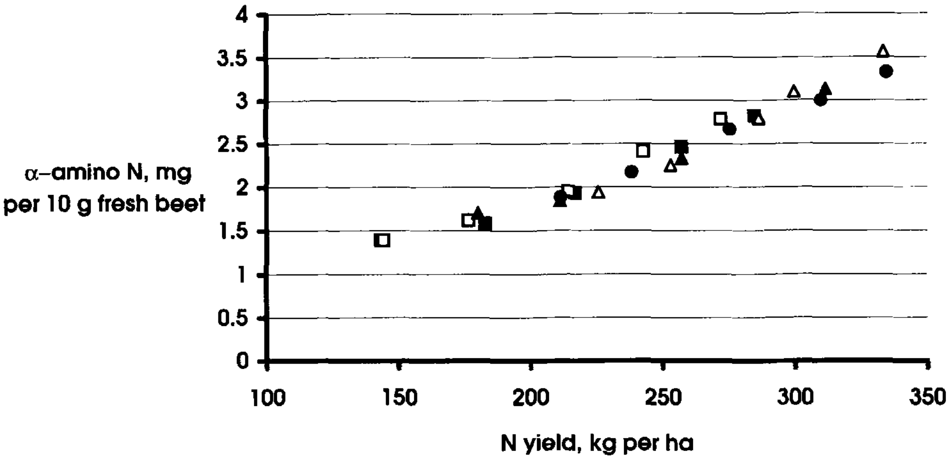


Figure 5. The α-amino N content of sugar beets as affected by the N yield (tops and leaves included) and the origin of the N (average of 7 experiments; ■ = fallow, □ = G0, ▲ = G100, △ = G200, ● = RC).

of time were not discerned. Effects after potatoes were not significantly different from those after sugar beets.

Discussion

N yields of undersown Italian ryegrass grown as a cover crop after cereals were markedly determined by the availability of N. Inputs of N were needed to exploit the production potential of Italian ryegrass, as cereals leave small amounts of residual

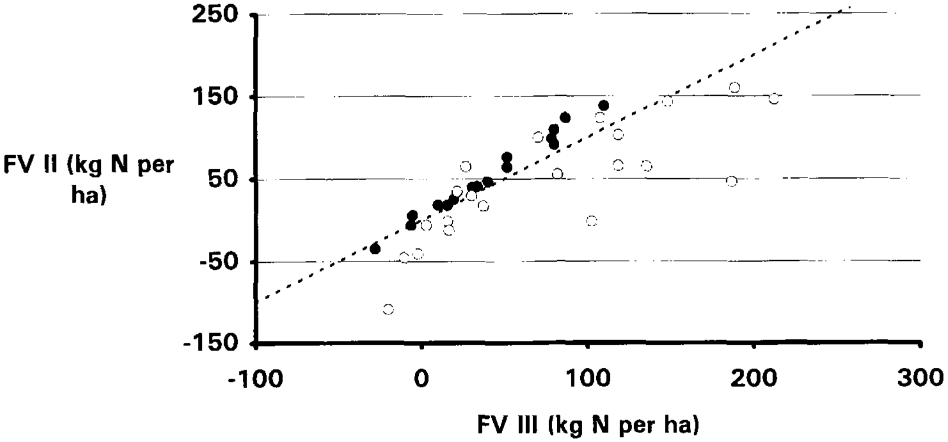


Figure 6. Relationship between the fertilizer value of cover crops calculated according to method III (FV$_{II}$) and method II (FV$_{III}$) for potatoes and sugar beets; ● = potatoes, ○ = sugar beets, ----- = 1:1 line.

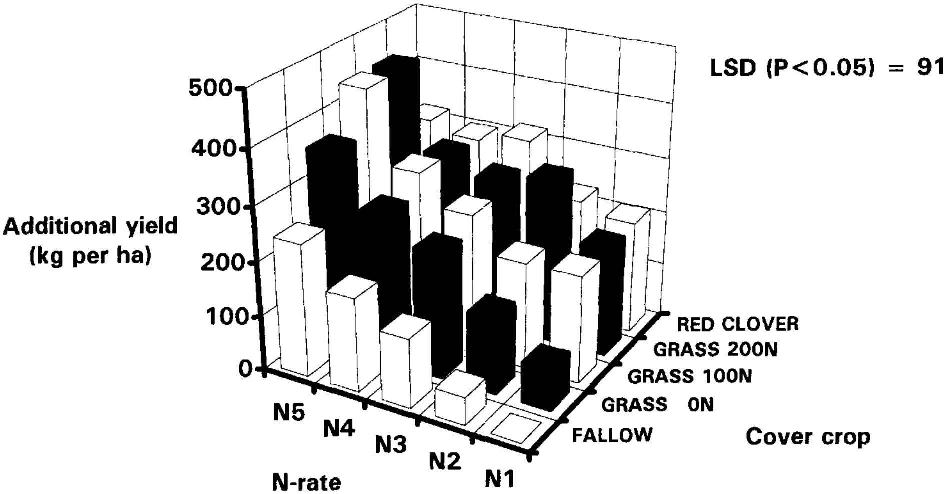


Figure 7. Residual effects of previous N fertilizer rates and cover crops on the grain yield of winter wheat (average of 9 experiments).

SMN (Neeteson, 1995; Schröder *et al.*, 1996). This implies that farmers can indeed use Italian ryegrass as a temporary storage for manure N which is commonly applied to cereal stubbles in The Netherlands.

Even with ample N, there was variation in N yield among years. This variation seemed to originate from the availability of moisture during the growing season of wheat rather than just from weather conditions after harvesting. Probably, undersown cover crops grew less vigourously when the top soil was not regularly rewetted by rainfall.

SMN in spring underestimated the N contribution of cover crops to following crops. Indicators other than SMN will be needed if farmers are to be convinced of the fertilizer value of cover crops. Fractioning the soil organic matter into density classes may provide better estimates of the N supplying capacity of soils (Hassink, 1995), but the magnitude of organic N inputs through cover crops is probably too small to make this technique work.

Withholding mineral fertilizer from Italian ryegrass resulted in N deficient cover crops which reduced the availability of N to following potatoes and sugar beets and depressed yields in some of the experiments. Fertilized Italian ryegrass, however, increased the availability of N during the next growing season. The apparent recovery of ryegrass N was largest for G200 followed by sugar beets. This may partly result from an incomplete recovery of the autumn applied fertilizer N to the G200 cover crop leading to a surplus of SMN, a partial carry-over of this surplus to the next spring, and the interception of this carried-over N by next year's deep rooting sugar beet crops. The amounts of fertilizer N apparently left unrecovered were 68 kg ha^{-1} larger for G200 than for G100 cover crops (Table 3). SMN measurements in four of the eleven experiments suggested that about 30 kg ha^{-1} of this surplus could still be detected in spring. If we cautiously assume that 15 kg ha^{-1} of the surplus is effectively transferred into the sugar beet crop instead of lost over winter, the calculated *apparent* recovery of the cover crop N by sugar beets, would appear to be 12% larger than is actually attributable to the cover crop itself. Correction for such a non-biological transfer would reduce the observed value of the recovery of N in G200 cover crops by sugar beets from 70% to 58%.

The apparent recovery of cover crop N by following crops inevitably reflects the combined effects of mineralization characteristics *per se*, the ability of a test crop to recover the mineralized N and the allocation of N to either harvested plant fractions or crop residues. The recovery of cover crop N by potatoes was, on average, lower than by sugar beets like N of any other source is used more efficiently by the latter crop (Prins *et al.*, 1988; Neeteson, 1995). This difference between potatoes and sugar beets was also illustrated by the apparent recovery values of fertilizer N in the present experiments. However, the larger recovery value for sugar beets may partly have resulted from the inclusion of leave N.

Assessment of the fertilizer value of cover crops, avoids the aforementioned shortcomings associated with apparent recoveries. Fertilizer values were lowest when defined as the difference in economic optimum N rate (Lory *et al.*, 1995). This method underestimates the difficulties encountered in a precise assessment of the economic optimum. The quadratic response functions that we used, tend to overestimate the optimum, especially when the response is flat as in case of cover crop treatments (Cerrato & Blackmer, 1990; Bullock & Bullock, 1994; Stecker *et al.*, 1995). Therefore, N fertilizer needs may have been overestimated and fertilizer values of cover crops may have been underestimated. Unfortunately, our experiments contained too few N rates to describe the response with a quadratic plus plateau models as proposed by Cerrato & Blackmer (1990). These complications made it difficult to use the difference in economic optimum N rate as and estimate for the fertilizer value. Lory *et al.* (1995) considered this estimate superior over other methods for the estimation of the fertilizer value, in situations where non-N effects were likely. Fortunately, evidence for such effects was lacking in our experiments.

The fertilizer value of cover crops was also calculated from their effects on the marketable and N yield when no further mineral fertilizer N was supplied. Fertilizer values according to these two methods were considerably larger than those based on the difference of the economic optimum N rates.

The fertilizer value of RC was almost double the amount of aboveground N that had been ploughed in. C to N ratios of clover roots are about 20, whereas the C to N ratios of roots from graminaeous species are usually more than 40 (Klimanek, 1990; Reeves *et al.*, 1993). Therefore, RC roots may have contributed considerably more to the N supply of following crops than the roots of Italian ryegrass. Consequently, the fertilizer value of RC was much larger than suggested by the aerial plant parts. The fertilizer value of fertilized Italian ryegrass was equivalent to about half the amount of N accumulated in the aerial plant parts. We presume that the large fertilizer values that were found for G200 cover crops were biased for reasons pointed out before. However, an increased N content in the roots of G200 cover crops may also have enlarged their fertilizer value.

Effects of cover crops persisted in the wheat crops that followed potatoes and sugar beets. Grain yields were increased by almost 100 kg ha^{-1} after G0 cover crops and by approximately 200 kg ha^{-1} after G100, G200 and RC cover crops. For the legume RC, also, this seemed a residual effect from previous RC crops rather than a direct N contribution from the present RC undersowing. Such a direct effect from a legume is unlikely (Hall, 1995). Moreover, the positive effect of RC on wheat yields was also observed in the last year of the four experiments when cover crops were no longer present. Assuming that wheat crops take up about 2.5 kg N per 100 kg grain with an apparent recovery of SMN of 70% (Van Keulen, 1986), the fertilizer value of cover crops during this stage of the rotation was 3 and 7 kg N ha^{-1} for G0 and the other three cover crop types, respectively. When these residual effects were also taken into account, the relative fertilizer value of a G0 cover crop changed from negative to neutral. For G100 cover crops it raised to a maximum value of 65%, leaving at least 35% of the aboveground cover crop N ineffective in terms of crop production in the first 18 months after incorporation. Combining this fertilizer value with the observed value of the recovery of fertilizer N by G100 cover crops, makes us conclude that approximately 55% of the mineral N initially applied to Italian ryegrass, was not benefitted from by either potatoes or sugar beets and the following winter wheat crop. This relative inefficiency may be partly due to denitrification losses occurring after the incorporation of ryegrass. This hypothesis was supported by the bluish colouring of the soil in the proximity of ryegrass residues.

N rates on preceding crops also had a residual effect, despite the removal of most crop residues. Apparently, residual SMN and N in leaves and stems of potatoes and in fibrous roots were partly transferred to the next season, confirming that the effects of applied (or withheld) N are not necessarily restricted to just one season (Vanotti *et al.*, 1995).

Our results indicate that cover crops can be a significant tool for the transfer of mineral N from one season to another. This may be of special relevance when manure is applied in late summer and autumn, and winters are mild and wet so that mineral N can be lost to a large extent without cover crops. If, however, the soil texture allows heavy field traffic in spring, postponement of manure application to spring is more likely to bring about a large availability of nutrients to summer crops than the application of manure in late summer combined with cover crops.

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